NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2576

A STUDY OF SLIP FORMATION IN POLYCRYSTALLINE ALUMINUM

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Washington
December 1951

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SUMMARY

Experimental results are presented which shed light on the assumptions that have been made in several attempts to bridge the gap between physical and mathematical theories of plasticity. The experimental results are compatible with, but do not necessarily verify, the conception that plastic deformation in strain-hardening materials is primarily due to slip. Slip was observed to occur first in a few isolated grains and to spread gradually to adjacent grains as the stress level increased. The occurrence and spread of the slip lines suggested independent behavior of randomly oriented grains at low stress levels with interaction among grains increasing as the stress level increased.

INTRODUCTION

For a number of years, the so-called "theory of plasticity" has been developing along two paths: mathematical and physical. The mathematical theory of plasticity is concerned with the polyaxial stress-strain relations of the material and the application of these relations to the solution of technological problems. The physical theory of plasticity is primarily concerned with the structure of matter and the physical processes associated with plastic deformation. In general, the stress-strain relations used in the mathematical theory of plasticity have been derived without reference to the physical origins of plasticity.

Several attempts have been made to correlate these two fields. In 1928 Sachs (reference 1) calculated the ratio of tensile yield stress to shear yield stress for a polycrystal of face-centered cubic crystal structure; the results were in good agreement with experiment and with the octahedral shear theory of yielding. The calculation by Sachs was based on the assumption that the component of shear stress on the active slip plane in the slip direction (that is, the resolved shear stress) in each grain is equal, and thus, when yielding occurs, all the grains in a randomly oriented polycrystalline aggregate simultaneously commence slipping along their most highly shear-stressed slip planes. In 1937 Cox and Sopwith (reference 2) made a similar calculation which confirmed the work of Sachs on aluminum and extended it to cover body-centered cubic materials.

In 1938 Taylor (reference 3) calculated the uniaxial stress-strain relation of polycrystalline aluminum from the known properties of the single crystal on the assumption that all crystals of the aggregate were subjected at all times to the identical strain, namely, the macroscopic longitudinal extensions and transverse contractions of the entire mass. Taylor considered the 12 modes of slip for the face-centered cubic system and, as a consequence of the assumption of identical strain, found that, in general, each grain of the material slipped in 5 of its 12 possible modes of slip.

In 1949 Batdorf and Budiansky (reference 4) advanced a theory for the polyaxial stress-strain relations of a polycrystalline strain-hardening metal. They assumed that slip in a grain is determined by the local macroscopic shear stress and the restraint imposed by its elastic neighbors and occurs first in those grains having slip planes and slip directions oriented parallel to the maximum shear stress in the material. This assumption, in effect, means that the plastic deformation of one grain does not influence the neighboring grains so that all grains which slip do so in accordance with the local macroscopic stress.

Thus, all these theories have in common the assumption that slip is the mechanism of plastic deformation but vary with respect to other assumptions. For convenience, these assumptions are given in chart form in table I. In order to help assess the relative validity of the contradictory assumptions and to correlate the assumptions with previous experimental work, a micrographic investigation was made of the behavior of an aluminum alloy (commercially pure 2S-O aluminum) in tension. A sequence of photomicrographs is presented which show the inception, development, and distribution of slip lines.

RESULTS AND DISCUSSION

Photomicrographs are presented which show the inception and development of slip bands in an aluminum tensile specimen as the strain was increased from 0 to about 3 percent. Figure 1 is a typical tensile stress-strain curve of the 2S-O material. Numbered circles in this figure indicate the strain levels at which the photomicrographs, reproduced as figures 2 to 12, were obtained from 2 of the specimens tested. Figures 2 to 10 show the inception and development of slip bands in one specimen as the tensile strain is increased from 0 to about 3 percent. Figures 11 and 12 are of a second specimen and were included as corroborative evidence of the distribution of slip in other specimens.

Although the behavior of surface grains is not identical with interior grains because they are not subjected to restraints on all sides as is the case of entirely enclosed grains, the assumption is made that the slip behavior of the surface grains under observation is reasonably representative of the interior grains. On the basis of this assumption the data of the present experiments can be used to shed light on the validity of the assumptions made with respect to a number of properties (a) mechanism of plastic deformation, (b) development of slip in a polycrystal, (c) number of slip systems in operation, and (d) equality of stresses or strains in all grains.

Mechanism of plastic deformation.- Sachs, Cox and Sopwith, Taylor, and Batdorf and Budiansky assume that slip is the mechanism responsible for plastic deformation. Boas and Hargreaves (reference 5) suggest that plastic deformation is due to slip and to a nonslip mechanism with a different stress-strain relationship. The nature of the nonslip process was not suggested by their experimental work. Slip is the only visually evident type of plastic deformation in the present experiments. If slip were the sole source of plastic deformation, however, slip lines should be evident as soon as the elastic limit of the material is exceeded. Slip was first observed on the photomicrograph (fig. 4) in which the stress was considerably beyond the elastic limit. Heidenreich and Shockley (reference 6), however, have pointed out that the slip bands visible under a light microscope constitute a collection of lamina approximately 200 Angstroms thick when viewed under an electron microscope. Since the attainable limit of resolution of a light microscope does not approach 200 Angstroms, slip bands involving a number of laminations could be present in the surface grains without being visually evident even though in the field of view. Thus, the experiments are compatible with, but do not necessarily verify, the assumption that plastic deformation is due to slip within the grains.

Development of slip in a polycrystal.- Sachs, Cox and Sopwith, and Taylor assumed that all grains deform simultaneously during plastic deformation so that slip lines should appear on all grains simultaneously. Batdorf and Budiansky, however, assumed that slip first occurs in a few randomly located grains, the remaining grains gradually becoming involved in a random fashion as the stress level rises. Figures 2 to 10 show that slip occurs first in isolated grains (the first slip appears not far from the edge of fig. 4 near the upper left-hand corner; other slips appear in the lower right-hand corner and upper center of fig. 5) in agreement with Batdorf and Budiansky and in contradiction to the assumptions of Sachs, Cox and Sopwith, and Taylor. As straining increases, however, there is a tendency for interaction among those grains which first suffered plastic deformation and their neighboring grains rather than for development in purely random fashion as assumed by Batdorf and Budiansky.

Number of slip systems in operation.- Taylor considered the 12 possible slip systems (in aluminum) and concluded that 5 slip systems (two slip directions in each of two slip planes, one slip direction in the third slip plane and no slip in the fourth slip plane) were generally in operation so that normally three sets of slip lines should be observable in each crystal. Sachs and Cox and Sopwith assumed and Batdorf and Budiansky implied that in proportional loading only one slip system would be active in each crystal. Thus, only one set of slip lines should be observable in any grain. In the present experiment, the observation of only one set of slip lines in any grain indicates that slip occurs on only one slip plane. This result, of course, does not preclude the possibility of slip in more than one direction in that plane. It should be pointed out, however, that in face-centered cubic metals double slip is occasionally noted and triple slip has also been reported. (See, for example, references 5 and 7.)

Equality of stresses or strains in all grains.- Taylor assumed the equality of microscopic and macroscopic strains; thus no explicit account was taken of the equilibrium of forces. Batdorf and Budiansky assumed equality of microscopic and macroscopic stress and, as a consequence, neglected to satisfy strain compatibility at the grain boundaries. Sachs and Cox and Sopwith assumed equality of resolved shear stress in all grains, an assumption which neglected both the requirement of equilibrium and that of compatibility. The present experiments indicate that microscopic and macroscopic strains are not identical since slip occurs in a single system and in individual grains irrespective of the surrounding grains. Neither is the assumption of identical microscopic and macroscopic stress valid as evidenced by the clumping action (that is, the deformation of the initially plastically deforming grain induced additional stresses in its neighboring grains and caused them to slip before they would have if influenced only by an elastic surrounding media). Boas and Hargreaves found by direct measurements of the deformations and hardnesses of various grains of a polycrystalline specimen that neither microscopic and macroscopic strains nor microscopic and macroscopic stresses were equal. The assumption of the equality of resolved shear stress in all grains is contradicted by the fact that slip does not occur simultaneously in all grains.

CONCLUDING REMARKS

Several attempts by theoretical methods have been made to help bridge the gap between the physical theory of plasticity and the mathematical theory of plasticity. The experimental investigation presented herein sheds light on the validity of some of the assumptions underlying these attempts.

The experimental results are compatible with, but do not necessarily verify, the conception that plastic deformation in strain-hardening materials is primarily due to slip. Slip was observed to occur first in a few isolated grains and to spread gradually to adjacent grains as the stress level increased, contrary to the assumption sometimes made that all grains slip simultaneously. The occurrence and spread of slip lines was of such a nature as to suggest independent behavior of randomly oriented grains at low stress levels with interaction among grains increasing as the stress level increased. Slip in only one slip plane in each grain was observed, a result in better agreement with the assumption that microscopic and macroscopic stresses are identical than with the assumption that microscopic and macroscopic strains are identical.

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National Advisory Committee for Aeronautics
Langley Field, Va., August 22, 1951

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TABLE I

ASSUMPTIONS OF SOME THEORETICAL ATTEMPTS TO CORRELATE

MATHEMATICAL AND PHYSICAL THEORIES OF PLASTICITY

Assumption \ Author	Sachs (reference 1) and Cox and Sopwith (reference 2)	Taylor (reference 3)	Batdorf and Budiansky (reference 4)
Mechanism of plastic deformation	Slip	Slip	Slip
Development of slip in a polycrystal	All grains slip simultaneously	All grains slip simultaneously	Grains start to slip one by one
Number of slip systems in operation	One	Five	One
Equality of stresses or strains in all grains	Resolved shear stresses equal	Strains equal	Stresses equal

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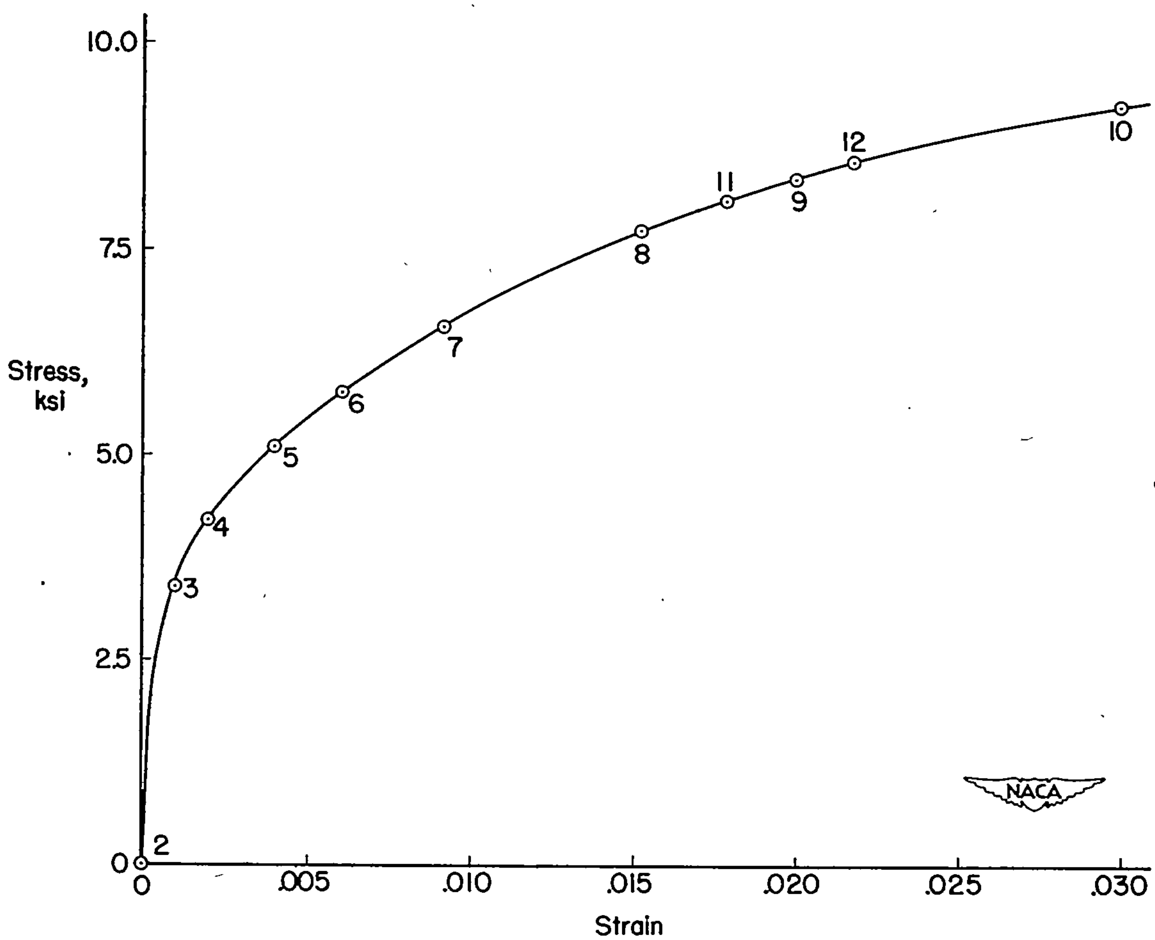


Figure 1.- Tensile stress-strain curve of 2S-O aluminum alloy showing strain levels of photomicrographs reproduced as figures 2 to 12. Numbers on the curve designate the strain levels of the indicated figures.

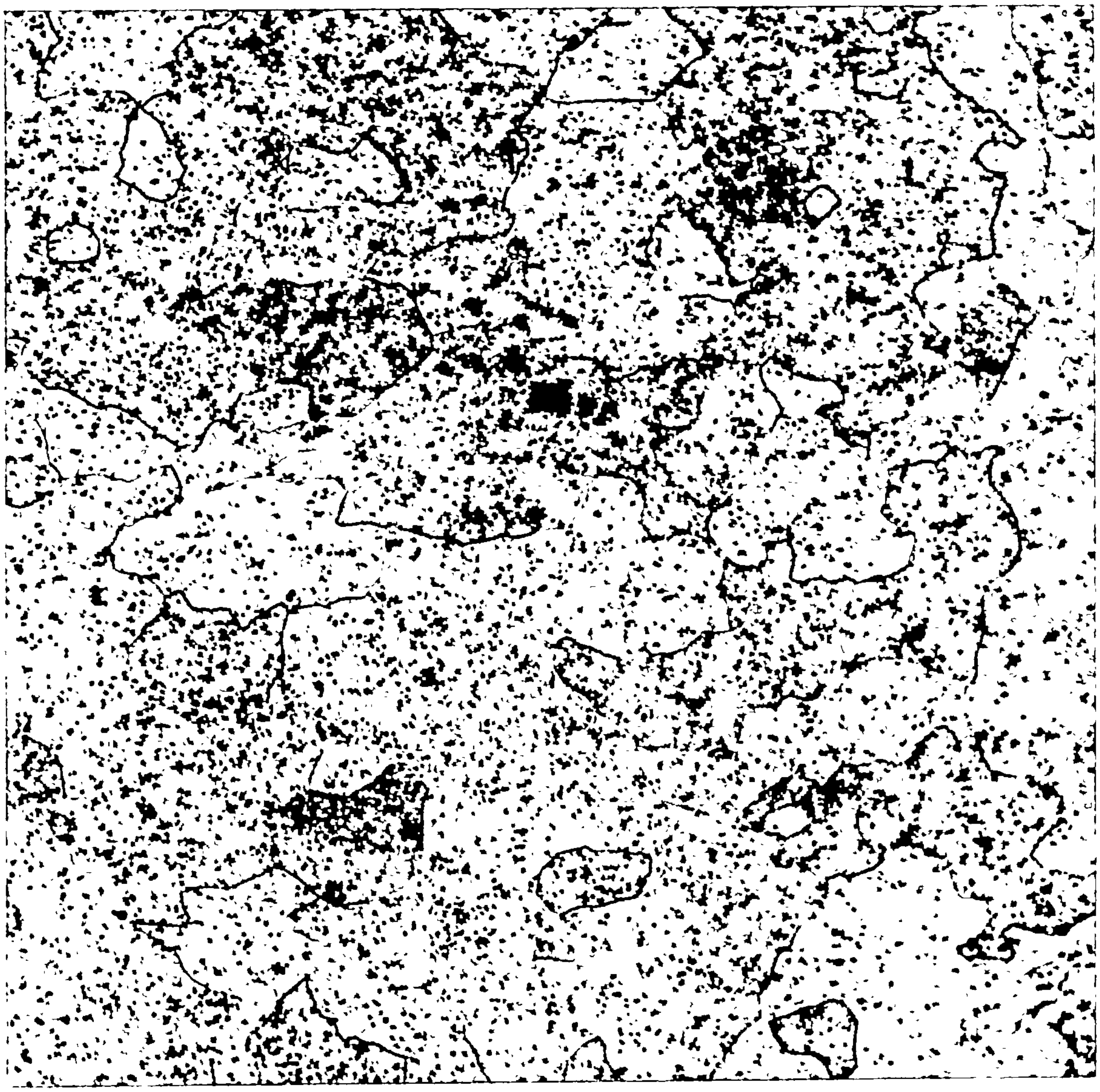


Figure 2.- Polished and etched surface of 2S-0 aluminum-alloy specimen 1 at zero strain. X350.

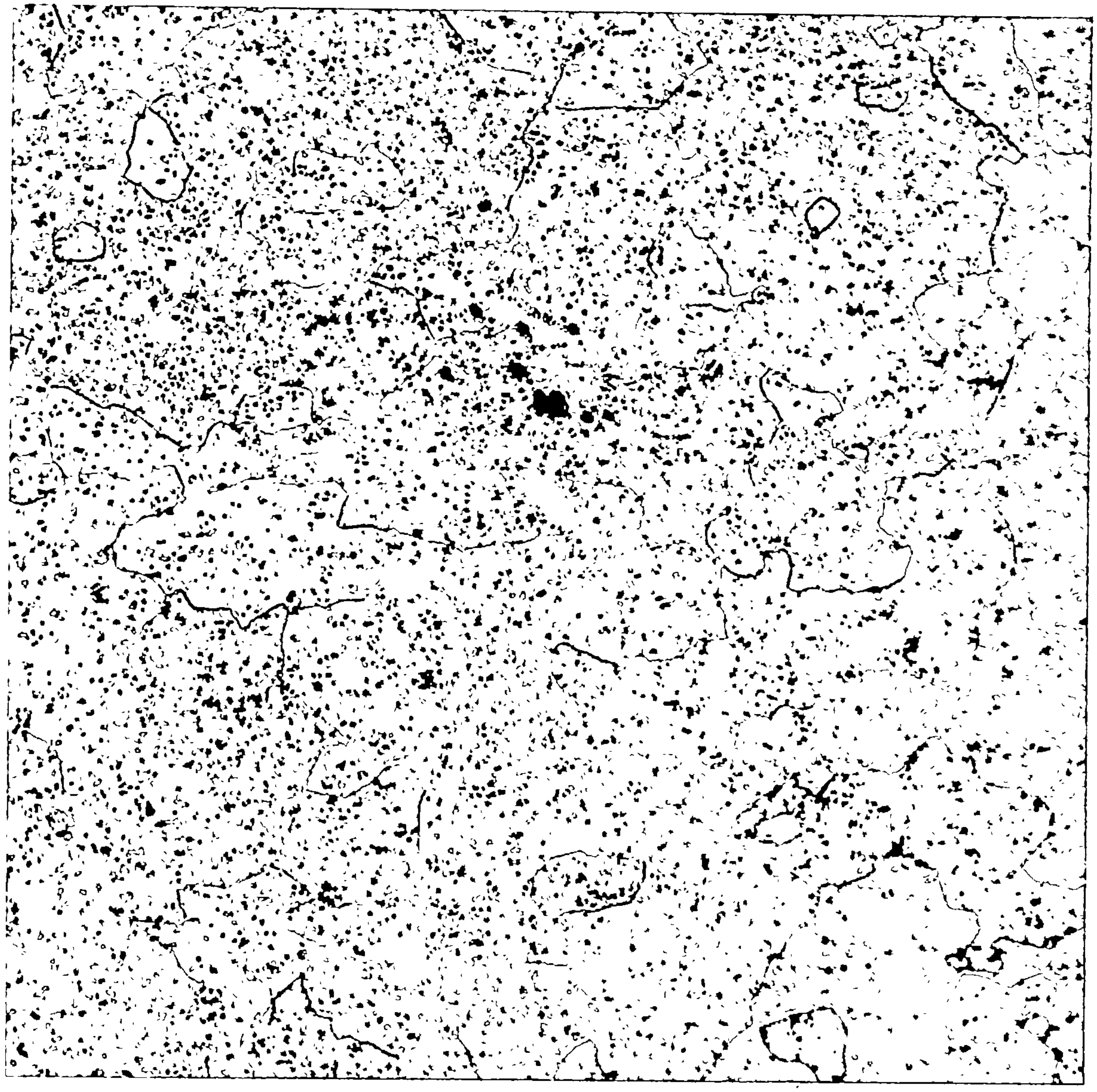


Figure 3.- Polished and etched surface of 2S-0 aluminum-alloy specimen 1 at 0.0010 strain. X350.

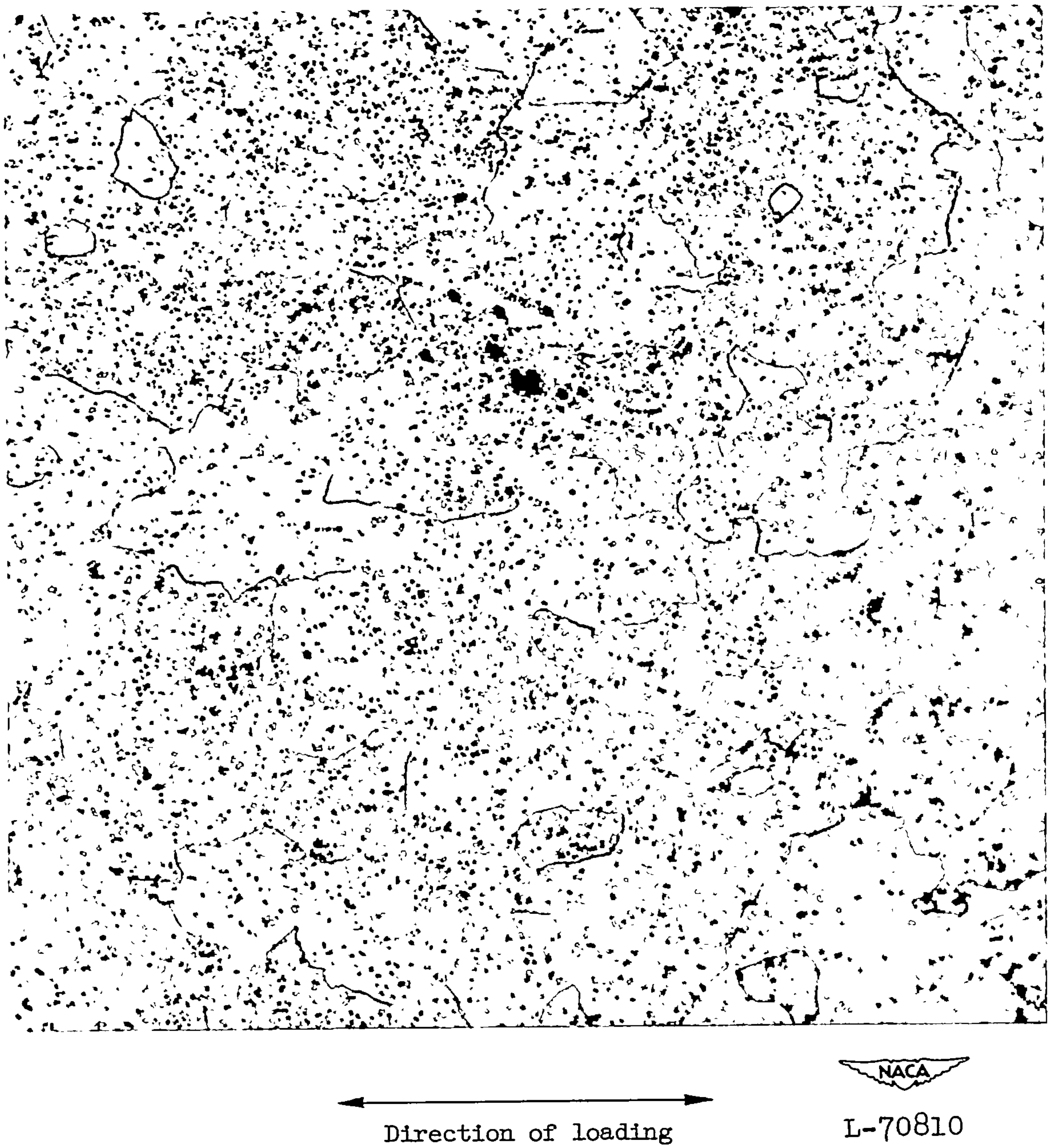


Figure 4.- Polished and etched surface of 2S-O aluminum-alloy specimen 1 at 0.0020 strain. X350.

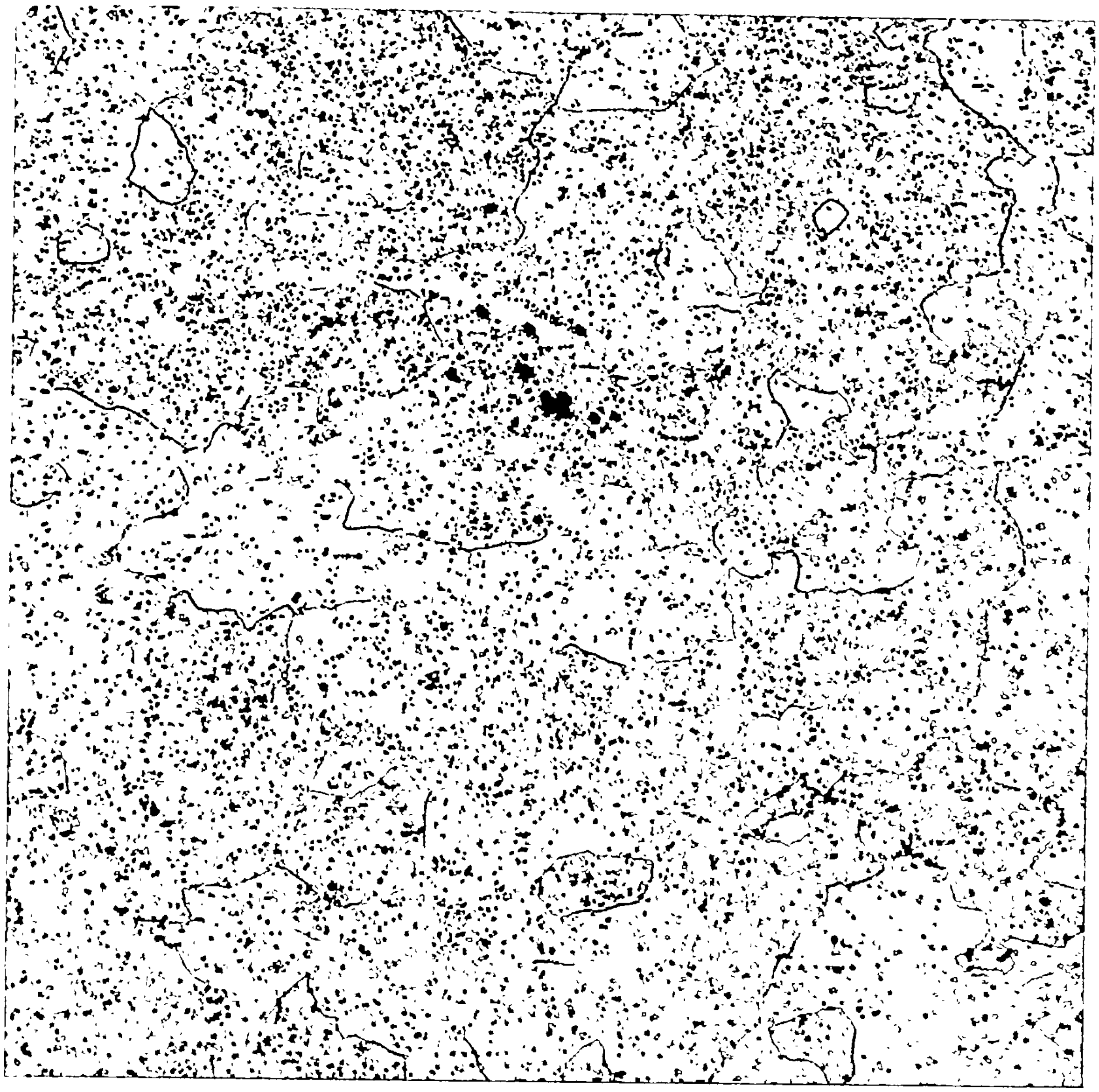


Figure 5.- Polished and etched surface of 2S-O aluminum-alloy specimen 1 at 0.0041 strain. X350.

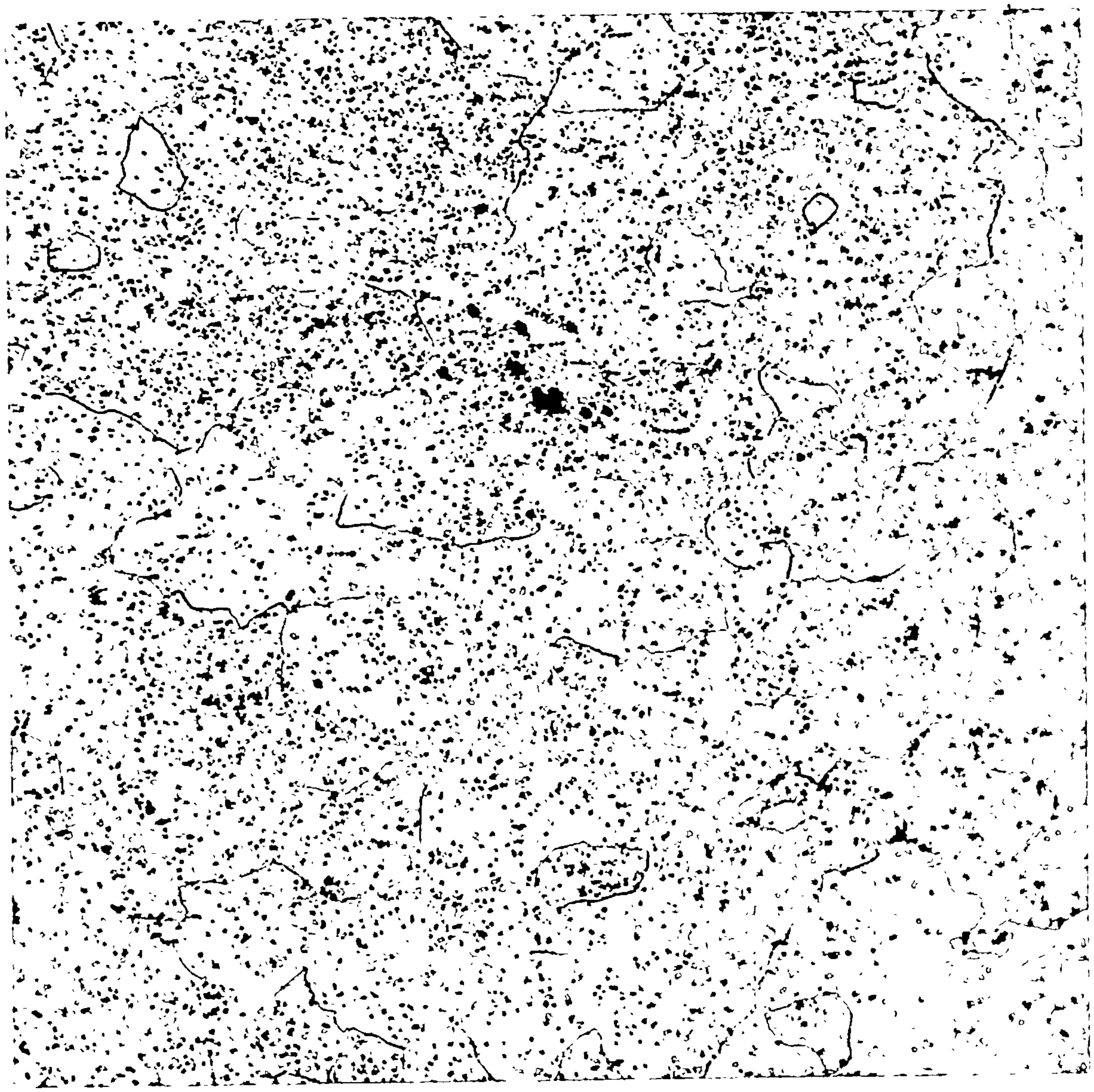
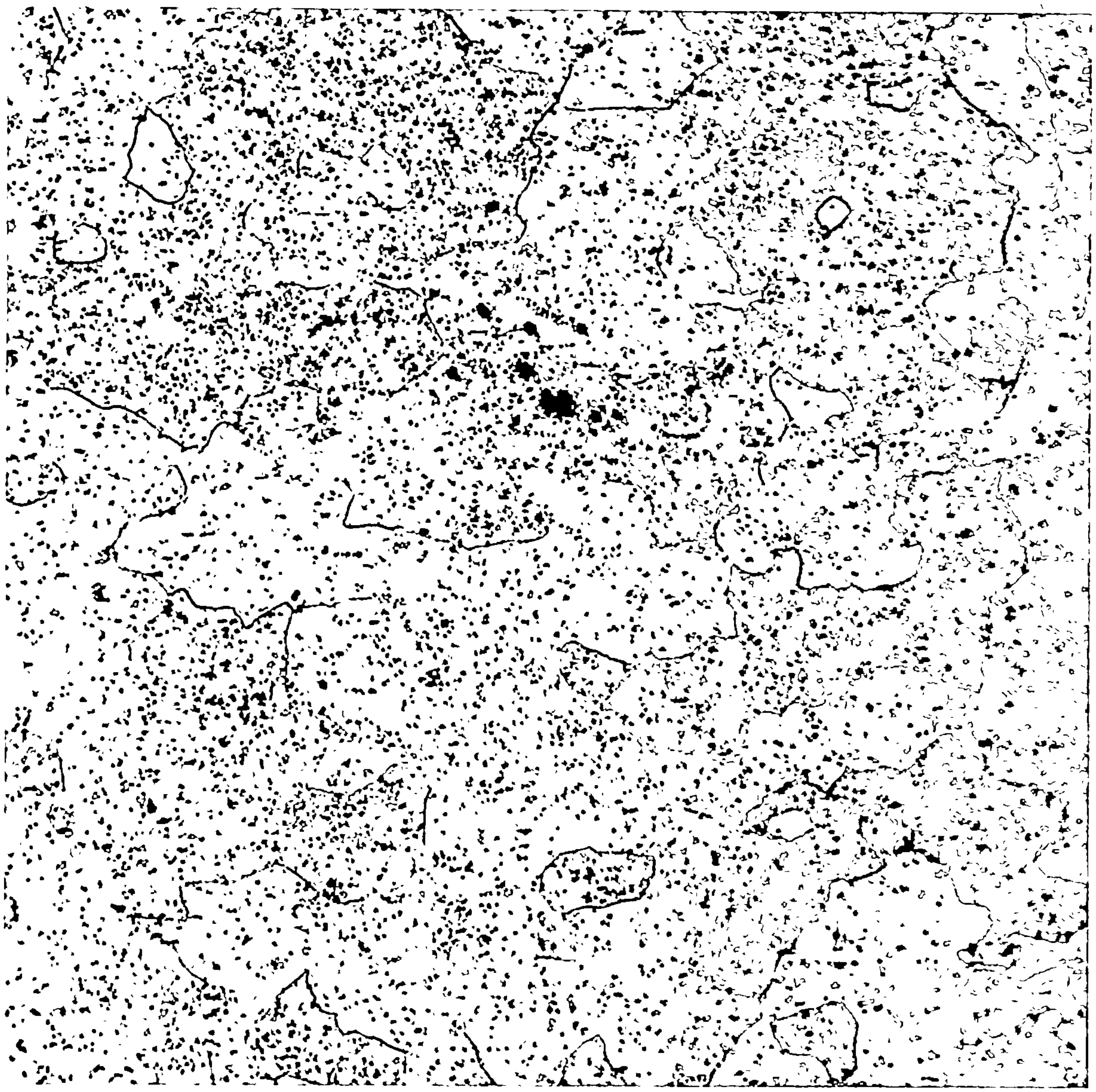


Figure 6.- Polished and etched surface of 2S-0 aluminum-alloy specimen 1 at 0.0063 strain. X350.



Direction of loading

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Figure 7.- Polished and etched surface of 2S-0 aluminum-alloy specimen 1 at 0.0092 strain. X350.

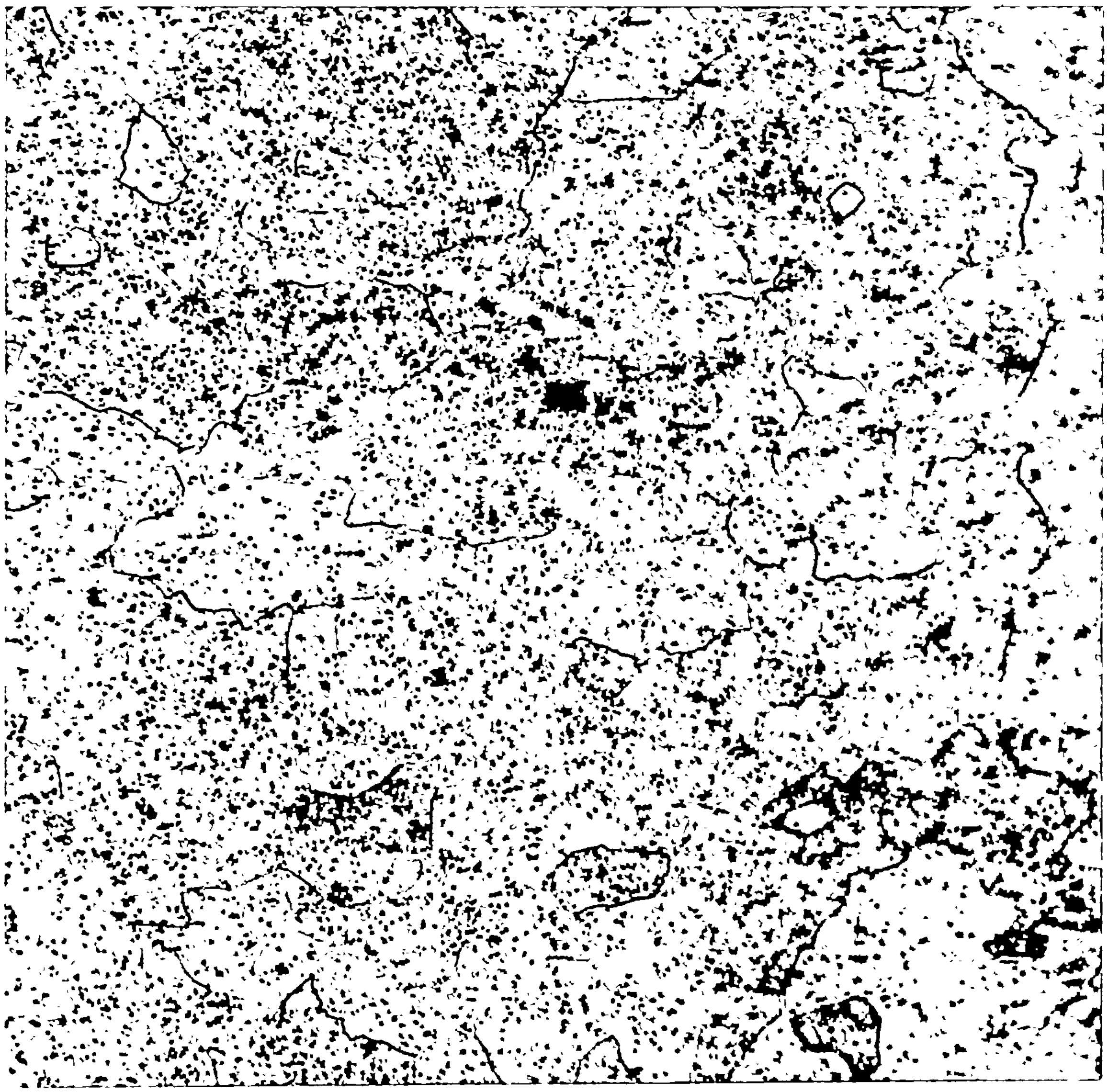
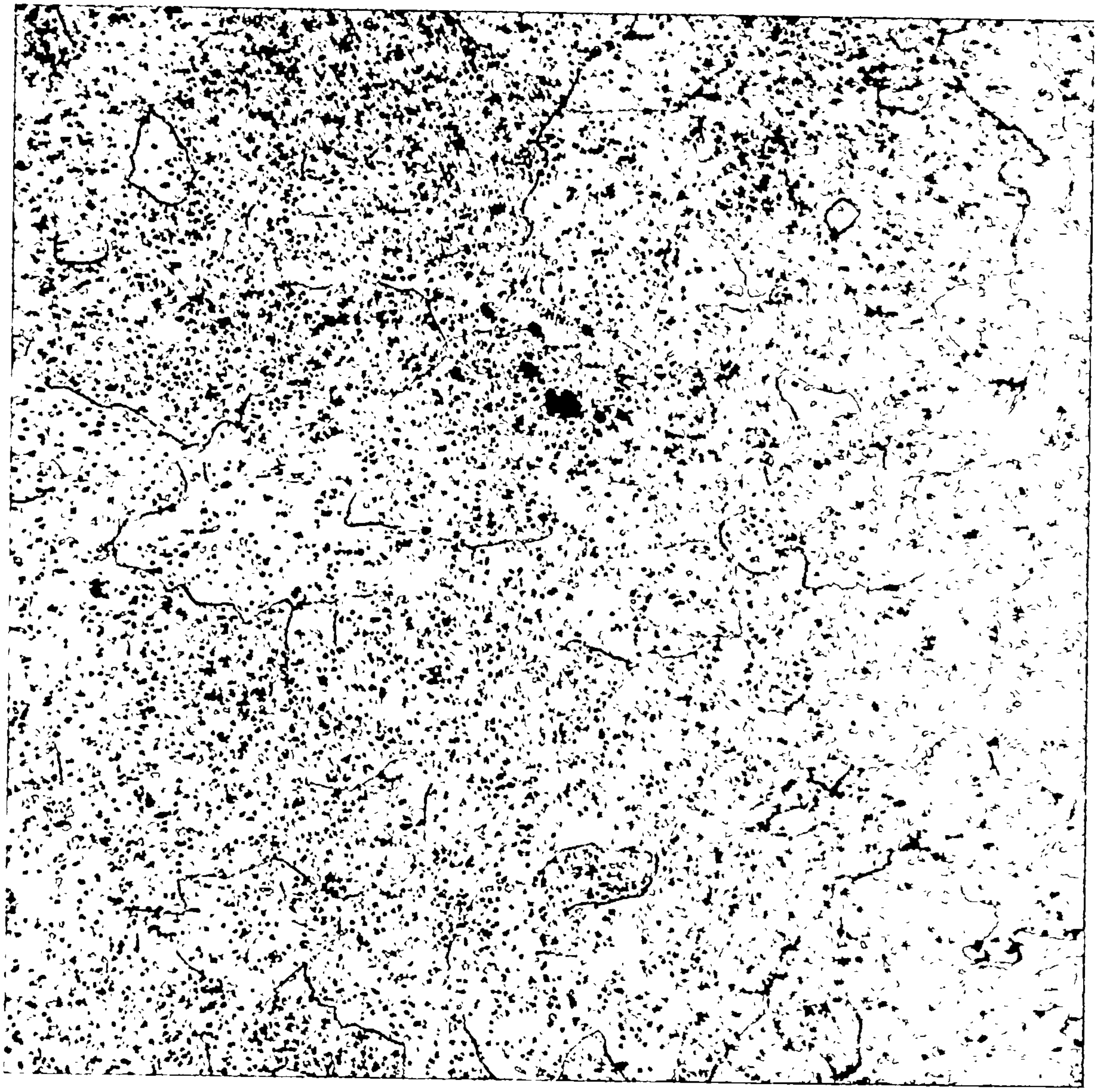


Figure 8.- Polished and etched surface of 2S-O aluminum-alloy specimen 1 at 0.0152 strain. X350.



Direction of loading

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Figure 9.- Polished and etched surface of 2S-0 aluminum-alloy specimen 1 at 0.0199 strain. X350.

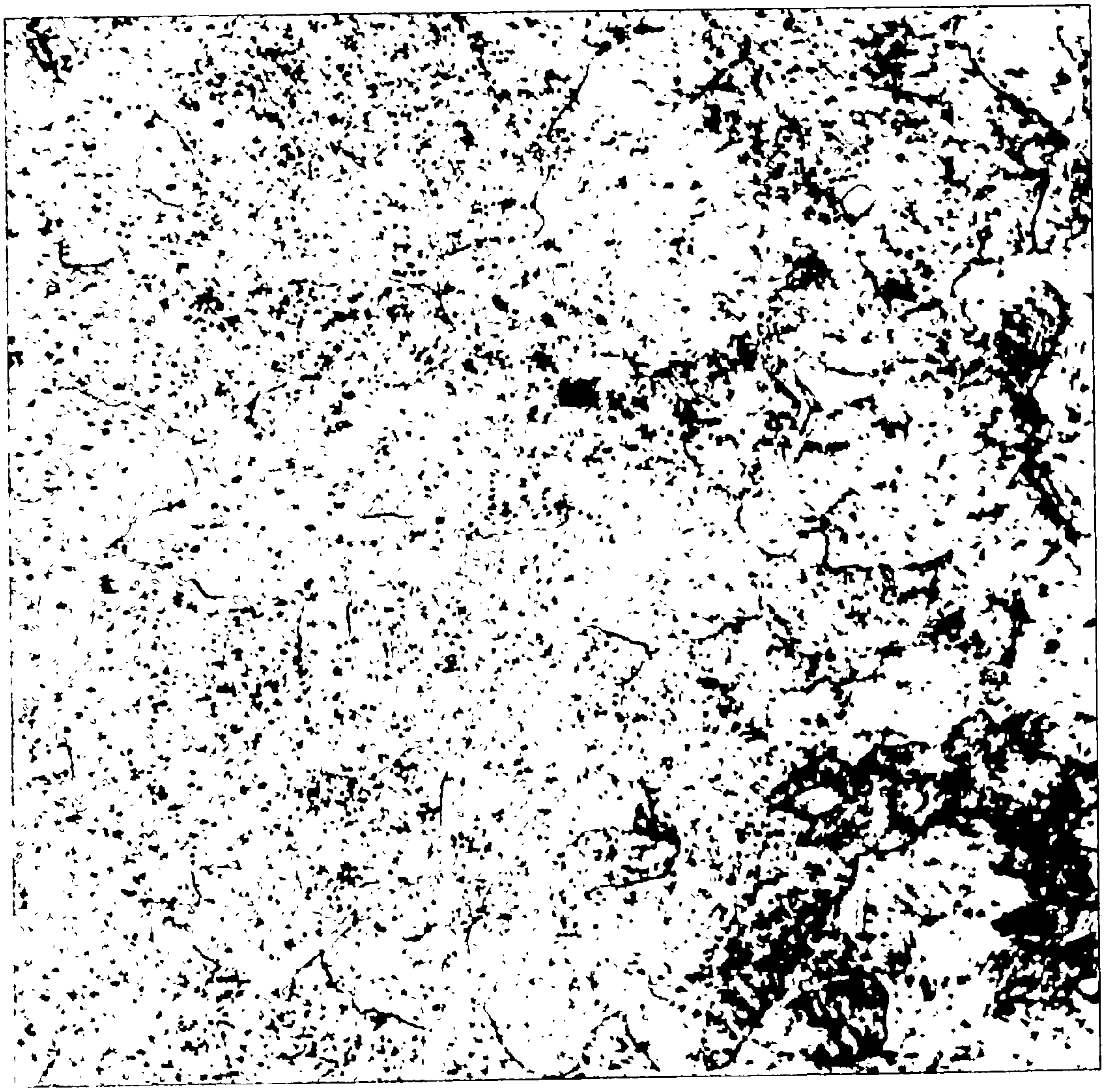


Figure 10.- Polished and etched surface of 2S-0 aluminum-alloy specimen 1 at 0.0300 strain. X350.

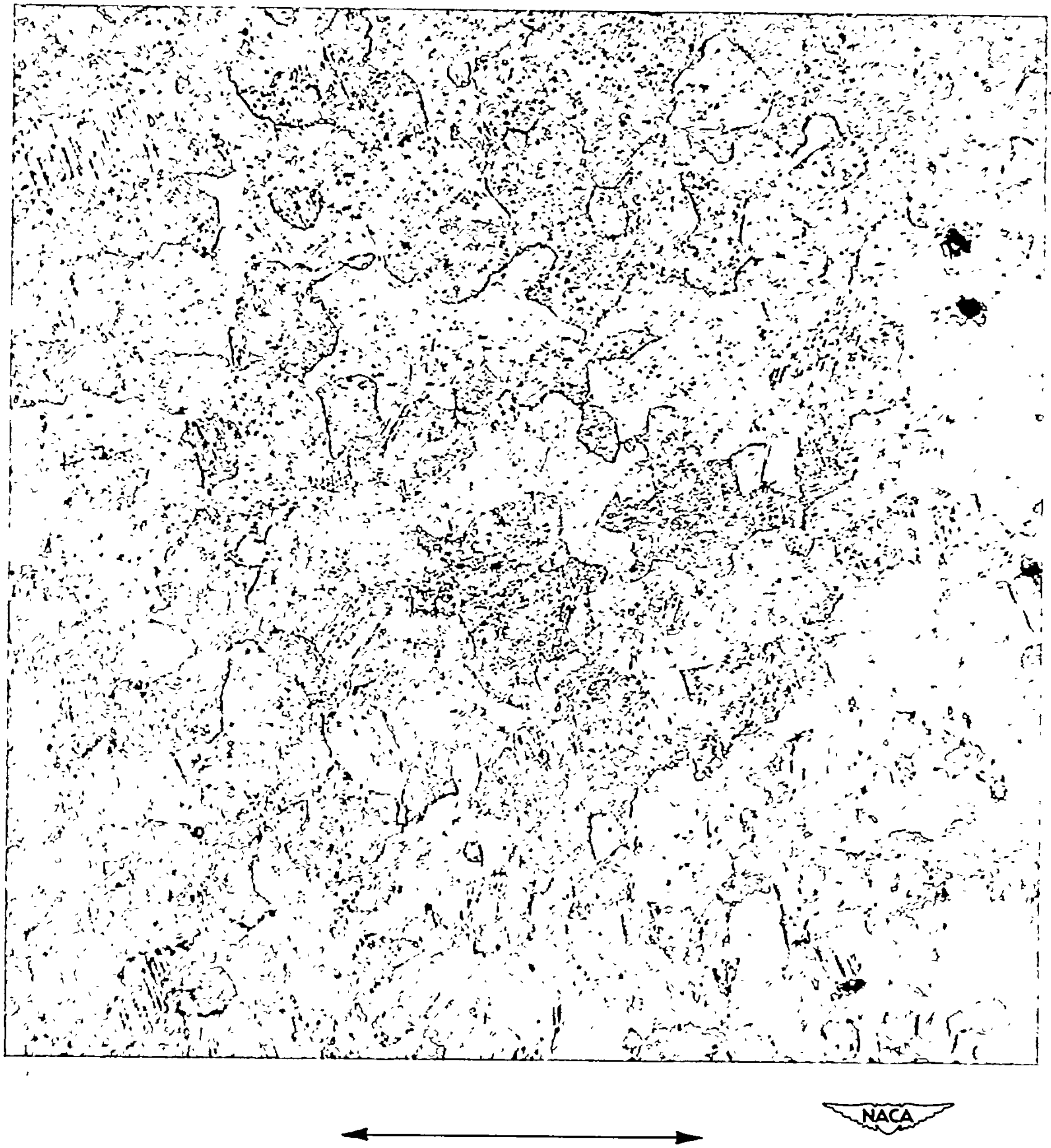
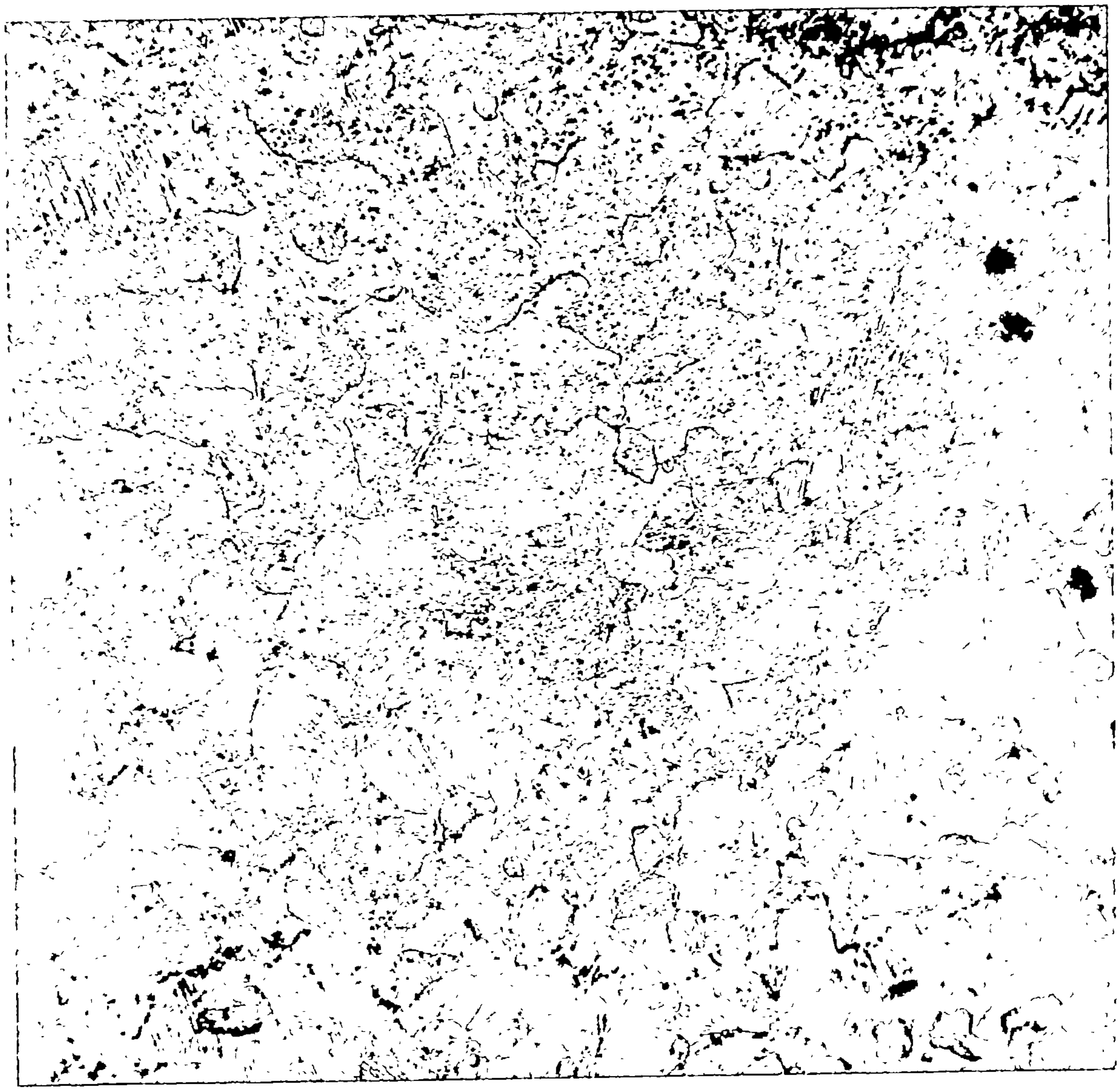


Figure 11.- Polished and etched surface of 2S-O aluminum-alloy specimen 2 at 0.0179 strain. X350.



Direction of loading

L-70818

Figure 12.- Polished and etched surface of 2S-0 aluminum-alloy specimen 2 at 0.0216 strain. X350.

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